Wave Walker

Phase I Final Report

N00014-94-C-0058

Document Number: 9324-REPT-001.1

Release Date: November 30, 1994

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Chapter 1: Problem Definition

Improved near shore mine detection and neutralization capability is needed by the U.S. Navy. Analysis of the littoral warfare mission and the Persian Gulf experience identified this need. The littoral warfare mission increases emphasis on near shore and amphibious operations.

Mine detection and neutralization involves a number of tasks and many efforts are underway to improve existing capabilities. The Office of Naval Research is using the SBIR program as part of these capability improvement activities. RedZone Robotics received a Phase 1 SBIR contract to develop a concept for a walking robot that can operate in near shore environments. This robot would be used to clear near shore areas of mines before an assault.

In operation, many robots would be released near the mine field with a general heading for the area to be cleared. The robots would proceed to spread out and canvas the area for mines. When a robot encountered a mine, it would stop and enter a wait mode. If other robots discovered the same mine, they would sense that a robot was already there in wait mode. When the area had been adequately covered, explosive charges in the robots would be detonated to destroy the mines and the robots.

Discussions with Office of Naval Research personnel led to the following requirements for the robot:

- The robots will be used to destroy mines underwater and on the beach. They will be released in groups from a submersible near a minefield and will travel through the minefield searching for mines. As mines are found, the robot will stop searching and position itself near the mine. At some later time, an explosive charge in the robot will be detonated destroying the mine and the robot.
- The robot is intended to operate in water depths of zero to 12.2 meters (40 feet) and travel 100+ meters (330+ ft). The water is assumed turbid limiting visibility and there will be no interfering animal or plant life.

- Minimal communications between the robot and other devices is expected. Detonation commands and communication to prevent all the robots from clustering around a single mine are possible.
- Robot life will be limited by on board energy storage but 4 to 8 hours is expected. Life will be affected by travel distance requirements.
- Robots should be as small as possible and present a compact package for transportation.

Certain aspects of the operating environment which are critical to the robot design were not specified. These include water velocity and direction, terrain geometry and soil strength characteristics. The literature was examined to try to develop a better understanding of these characteristics.

Water movement is produced by two sources: wave motion and currents. Based on the literature review, we assumed that a reasonable maximum water velocity was 6 knots for robot operations.

Terrain geometries and soil strength characteristics vary widely in near shore areas. The literature review did not produce a useful set of terrain and soil properties. Therefore, we assumed that the operating environment conditions would be bounded by the limits imposed for successful amphibious landing operations. This excluded very difficult terrain. The ability to move on slopes and through obstacles was considered during concept assessment.

Chapter 2: Concept Selection

This chapter presents the multi-step process used to select a robot concept. First, through brainstorming sessions, we generated an extensive list of concepts. Although the ideas were not very well developed, we characterized them well enough to be able to judge their relative merits. Next, we reduced the concept number by removing unlikely ideas and combining similar ideas into groups. This produced a list of concept finalists. Finally, the Pugh methodology was then used to select the best concept from the finalists. Section 2.1 discusses the criteria we used to evaluate the concepts. Section 2.2 presents the concept finalists.

2.1 Selection Criteria

The selection criteria used for the evaluation were:

Robot cost - the total cost of one robot

Control complexity - the intelligence required to operate the robot

Energy consumption - the amount of energy required to move a distance

Maximum travel velocity - the top traveling speed of the system

Stability - the ability of the robot to maintain itself upright or right itself

Maneuverability - the ability of the robot to handle rough terrain

Ease of waterproofing - the ability to seal the system against sea water

These selection criteria cannot be directly applied to the robot concepts since little more than the fundamental attributes of each concept are known at this stage. Therefore, the selection criteria were analyzed to determine how each criteria was affected by fundamental robot attributes which could more easily be applied to the concepts. Details of this analysis are shown in Appendix A. This analysis produced the following criteria which were used for concept selection:

Total number of leg links

Leg link complexity

Total number of actuators

Number of coordinated actuator motions to achieve movement

Open or closed loop control of actuators

Vertical oscillation of body mass during movement

Friction during movement

Stride length

Drag area of leg links

Total weight/foot size (for legs in contact)

Ease of sealing out water (rotary actuators are easier to seal)

2.2 Concept Finalists

The eight finalists identified out of the original list of concepts are described below.

Four independent legs (non-redundant)

This concept is the classic articulated leg walking robot. The robot body is supported by four legs, each with three degrees of freedom. One statically stable gait is possible. One leg is lifted, moved to a new position and lowered into ground contact. The robot body is then shifted to a new position by moving all leg actuators while all the legs remain in contact with the ground. The motions of the twelve leg actuators must be coordinated to achieve movement. Rotary joints and actuators would be used to improve water sealing. Foot contact force sensing is very likely required to maintain stability.

Five or six independent legs (redundant)

This concept is the classic articulated leg walking robot with extra legs. The extra legs improve stability and increase control complexity. Each leg has three degrees of freedom. Several statically stable gaits are possible, lifting one, two or three legs simultaneously. The legs are lifted, moved to new positions and lowered into ground contact. The robot body is then shifted to a new position by moving all leg actuators while all the legs remain in contact with the ground. The motions of all of the leg actuators must be coordinated to achieve movement. Rotary joints and actuators would be used to improve water sealing. Foot contact force sensing is likely required to maintain stability.

Beam walker (two four legged moving platforms)

This concept is the classic beam walker robot. Two orthogonal translation platforms each with four legs alternately support the robot body to allow for movement in a series of X and/or Y translations. The feet on one platform are raised leaving the robot body supported by the legs on the other platform. The raised leg platform is translated to a new position and its legs lowered to support the robot body. The legs on the other platform are raised and the robot body and other platform translate to a new position along the platform axis.

R-theta device

This is a beam walker robot variant. One of the four legged translation platforms is merged into the robot body. The other translation platform is connected to the robot body with a rotary joint allowing rotation of the translation platform about a vertical axis. The translation platform rotates about a vertical axis on the robot body to change direction of movement. Robot movement occurs in a series of translations and/or platform rotation motions. The feet on the body and translation platform are alternately raised and lowered to allow movement.

Eight straight line motion legs

A. Motion parallel to mounting surface (Robert's and Tchebicheff's)

B. Motion perpendicular to mounting surface (Sarrut's or scissors)

This is a family of beam walker robot mechanism variants. Each translation platform is replaced by an opposed set of straight line motion linkages. The linkages can be mechanically interconnected to give the same function as the translation platform or an actuator can be added to give added flexibility in leg positioning. The legs are attached to the straight line motion linkages. Robot movement is produced by the same sequence of leg and body movements as the beam walker. Opposing pairs of legs alternately support the robot body to allow for translation in a series of X and/or Y movements.

There are two linkage families that can produce the desired straight line motion. In family "A", the Robert's and Tchebicheff's linkages produce straight line motion parallel to the linkage mounting points on the robot body. In family "B" the Sarrut's and scissors linkages produce straight line motion perpendicular to the linkage mounting points on the robot body.

Alternate R-theta

This combines the R-theta beam walker with straight line motion linkages. A set of straight line motion linkages replace the translation platform. Four legs are attached to the robot body and four legs are attached to the straight line motion linkages. The support for the opposed set of straight line motion linkages is connected to the robot body with a rotary joint allowing rotation about a vertical axis. Robot movement occurs in a series of translations and/or rotation motions. The linkages can be mechanically interconnected to give the same functionality as the beam walker translation platform or an actuator can be added to give added flexibility in positioning of the legs. The legs are attached to these linkages. The body legs and straight line motion linkage legs are raised and lowered alternately to allow movement.

"D" mechanism legs

This is another variant of the beam walker robot mechanism. Each translation platform is replaced by an opposed set of "D" motion linkages. The "D" motion linkage is a four bar linkage whose proportions result in an output link path shaped like the letter "D" when the input link is rotated. In this application, the linkage would be configured to place the straight segment of the "D" horizontal. The "D" motion linkage produces the required vertical and horizontal motions of the legs with a single actuator. The legs are attached to these linkages. The home position of the robot is with both sets of legs lifted near the midpoint of the "D" and the robot body resting on the surface. When movement is desired, the actuator is energized and one set of legs moves forward and down, lifting the robot body and other leg set off the surface. As the "D" motion linkage continues to move, the robot body and other leg set translate forward. As the "D" motion linkage nears the completion of its cycle, the robot body and other leg set are lowered to surface contact. The opposing pairs of legs alternately support the robot body to allow for translation in a series of X and Y movements. This mechanism produces a fixed stride length and vertical robot body motion.

Tail dragger (two legs extend and drag the robot body along the surface)

This is a simpler robot concept where two legs on robot body extend and drag the robot body along the surface. It requires a smaller space envelope but has some reduction in mobility. From the home position, the legs lift the feet off the ground. The legs and feet are then extended. The feet are lowered past the point of surface contact to raise the front of the robot body. The legs are then retracted to drag the robot body forward. Changing direction would be accomplished by using differential foot motion or, the two legs could be attached to a support which would rotate about a vertical axis on the robot body.

2.3 Concept Selection

The final step of concept selection was done using the Pugh methodology. The Pugh methodology uses one of the concepts as the reference and compares the other concepts to the reference for each of the selection criteria. The results of this analysis are summarized in the following three tables.

Table 2.1 quantifies concept characteristics for each selection criteria. Two criteria were left out of this analysis. Stride length was ignored since it was presumed that any concept could be given roughly equivalent stride length. The drag area of the leg links was ignored as it was difficult to judge relative advantages without significant further concept development. Table 2.2 shows the results of the Pugh process for the ten finalists using the four leg configuration as the reference.

	4 legs	5/6 legs	Beam Walk	R-Theta	8 legs Type A	8 legs Type B	Alt.R-Theta	D-Step	Tail-drag
# of leg links	12	15,18	10	10	36,62	24,26	11,12	22	4,5
Leg link complexity	med	med	med	M to H	L to M	med	M to H	med	med
Number of actuators	12	15,18	10	10	10,12	10,12	10,11	10	4,5
# of coord. motions	3,12	15,18	0	0	0,1	0,1	0,1	0	0
Open or closed loop	close	close	open	open	???	???	???	open	open
Oscillation of body	no	no	no	no	no	no	no	yes	yes
Friction	no	no	no	no	no	no	no	no	yes
Foot loading	W/3	W/4	W/4	W/4	W/4	W/4	W/4	W/4	???
Ease of sealing	rotary	rotary	linear	half	half	half	half	half	half

Table 2.1 Concept characteristics

	4 legs	5/6 legs	Beam Walk	R-Theta	8 legs Type A	8 legs Type B	Alt.R-Theta	D-Step	Tail-drag
# of leg links	0	-2.8	0.2	0.2	-4.1	-2.4	0	-1.8	0.6
Leg link complexity	0	0	0	-1	1	0	-1	0	0
Number of actuators	0	-2.8	0.2	0.2	0.1	0.1	0.1	0.2	0.6
# of coord. motions	0	-2.2	1	1	0.9	0.9	0.9	1	1
Open or closed loop	0	0	1	1	?	?	?	1	1
Oscillation of body	0	0	0	0	0	0	0	-1	-1
Friction	0	0	0	0	0	0	0	0	-1
Foot loading	0	0.3	0.3	0.3	0.3	0.3	0.3	0.3	?
Ease of sealing	0	0	-1	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Sum	0	-7.5	1.7	1.2	-2.3	-1.6	-0.2	-0.8	0.7

Table 2.2 Pugh analysis first iteration

Based on the above results the analysis was performed again, this time using only the highest scoring concepts from the first iteration. The beam walker concept was used as reference for the second iteration. The results are shown in Table 2.3.

	Beam Walk	R-Theta	Tail-drag
# of leg links	0	0	0.5
Leg link complexity	0	-0.5	0
Number of actuators	0	0	0.5
# of coord. motions	0	0	0
Open or closed loop	0	0	0
Oscillation of body	0	0	-1
Friction	0	0	-1
Foot loading	0	0	?
Ease of sealing	0	0	0.5
Sum	0	-0.5	-0.5

Table 2.3 Pugh analysis second iteration

Based on this analysis we proceeded with a preliminary design of the beam walker system. This design is presented in Chapter 3.

Chapter 3: Preliminary Design

This chapter presents a preliminary design and analysis of the beam walker concept. A leg concept was selected and sized, an energy storage method was selected, energy consumption during walking was estimated, the robot body was sized and stability was assessed. Efforts were made to be conservative throughout this process.

From the energy consumption estimate, we determined that hydrodynamic drag was a large factor in energy consumption for the beam walker. We reexamined the concept finalists for concepts with lower hydrodynamic drag. The tail dragger concept had lower drag potential so we also completed a preliminary design for it.

3.1 Beam Walker Overview

A beam walker capable of moving under its own power requires lightweight construction, powerful batteries, and energy-efficient motors and mechanisms. Lightweight construction is a function of materials selection and loading efficiency. Gear reduction allows motors driven at more efficient higher speeds; orthogonal leg axes and rolling (vs. sliding) friction joints enhance mechanism efficiency. Power consumption is reduced using low drag component shapes, actuating motors one at a time, and by making slow moves.

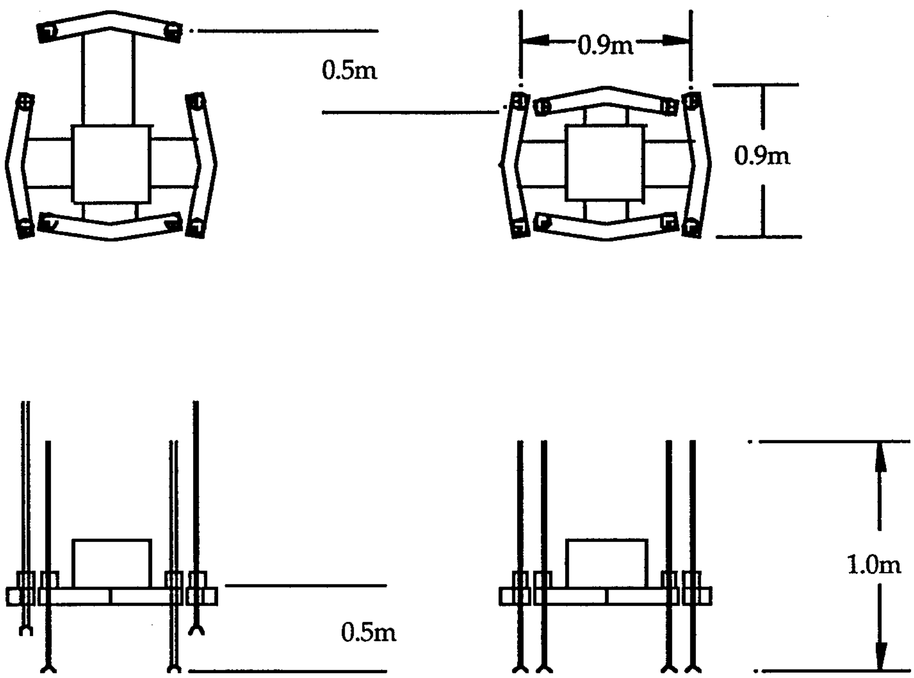

Figure 3.1 Beam walker

Our preliminary beam walker design weighs 86 kg (190 lbf) and can travel 100 m (330 ft) in six hours. It is believed that an optimal mine-seeking walker may weigh less. A preliminary set of specifications is shown in Table 3.1. Weight, cost, and other requirements of mine-detecting sensors, communication devices, and navigation systems may affect estimates. This study primarily illustrates the system required for the walking task.

Parameter	
Robot weight in air	86 kg (190 lbm)
Robot volume	0.9 m x 0.9 m x 0.9 m (3 ft x 3 ft x 3 ft)
Operating depth	0-12 meters below the ocean surface
Maximum incline	up to 45 degrees
Operating soils	Sand, gravel, mud, rock
Maximum currents	0-3 m/s (0-6 knot) any direction
Operating temperature range	0-40°C (32-100°F)
System life	6.0 hours
Max step length	0.5 m (20 in)
Nominal step speed	1.8 minutes per step
Max obstacle dimension	0.25 meter diameter
Number of feet/legs/frames	8 feet/8 legs/2 frames
Power requirement	983 kJ (273W-hr)
Power source	Lead acid battery
Battery voltage	24 VDC

Table 3.1 Preliminary specifications

Using the same gait for every step and limiting sensing requirements minimizes computation and system complexity. The batteries, electronics, sensors, and explosive are mounted within the space frame body; a low drag skin reduces body drag.

In severe current the robot may enhance stability by lowering the body. If the robot flips, feet could be mounted on the opposite end of the legs allow to complete its mission while upside down. Likely sensors carried onboard include:

1. mine detectors and rangers
2. compass and distance meter for dead reckoning navigation
3. body bumpers on four sides to detect obstacles
4. force-actuated foot switch to detect sea floor contact
5. current and voltage meters at the battery output to detect performance and remaining life
6. a two-axis tilt sensor to detect sea floor slope and tip over
7. communications capability with other Wave Walkers, and possibly for control of detonation
8. possible tamper detection devices
9. possible depth detector
10. vari-directional flow speed sensor

3.2 Walking Gait/Mechanism

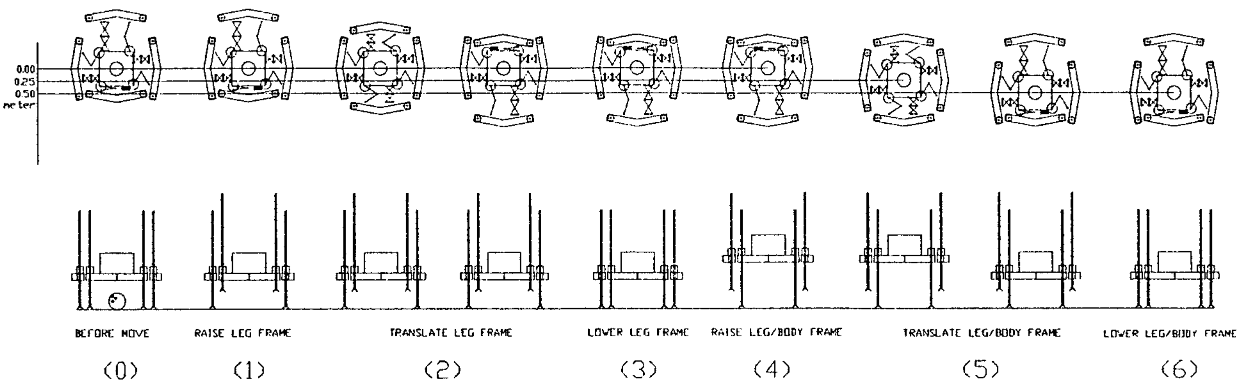

Figure 3.2 **The 6-step gait**

The 6-step gait provides one stride as illustrated in Figure 3.2. Each stride includes:

1. Raise four legs on moving frame
2. Translate the moving frame (all four legs are connected)
3. Lower the legs, allowing them to drop unpowered
4. Raise the legs and body
5. Translate the legs and body
6. Lower the legs and body

Leg Lift Mechanism

Gait moves (1), (3), (4), and (6) define leg lifting requirements. The legs are made of square mechanical tubing. Each leg is supported by rolling bearings on three sides and driven in by a small rack fastened to one side. A drive pinion, driven by a geared motor, engages the rack to move the leg. A brake at the motor fixes the leg when not in motion.

Frame Translate Mechanism
Gait moves (2) and (5) define frame translate requirements. There are eight legs, on four leg assemblies, two which translate in the x-direction and two in the y-direction. Each leg assembly is connected to the main body by a Sarrut's mechanism—two hinge joints mounted at right angles—providing linear motion (similar to a scissors mechanism). A cable drive actuates the leg assemblies in and out. The cable take-up reel is driven by a geared motor with a normally-closed brake which engages at the end of motion.

3.3 Energy Storage Method

A variety of energy storage methods were considered for the system. Factors of energy storage density, availability, cost and compatibility with an electric robot drive system were considered in the selection. Possible energy storage devices fall into three broad categories: mechanical storage (compressed air, flywheels, etc.), electrochemical (batteries, fuel cells) and mechanical-chemical (internal combustion engines, etc.). Mechanical energy storage devices have low energy storage densities. At best, they approach low performance batteries. Mechanical-chemical energy storage devices have high energy storage densities but require complex hardware which would be incompatible with the mission and size of this robot. Electrochemical energy storage devices fill the middle ground. Energy storage densities are reasonable and they are compatible with an electric robot drive system.

Many electrochemical energy storage devices exist. Different devices are at varying stages of development ranging from laboratory prototype to commercially available. Substantial resources are being used to bring new devices to market and to improve the performance of existing devices. In this design we chose lead acid batteries because their performance is well understood and they are inexpensive.

The modest energy storage density of lead acid batteries was considered an advantage for robot conceptual design. If robot performance was acceptable using lead acid batteries, improvements in robot range could easily be achieved by substituting other battery systems with higher energy storage densities such as Silver Oxide/Zinc or Lithium/Cobalt Oxide. This decision supported the goal of a conservatively designed robot system.

3.4 Walking Energy Consumption Estimate

Three steps was used to estimate walking energy consumption. The first step was to estimate the mechanical energy required to complete one stride. A stride is the sequence of movements to move the robot forward one stride and return it to its initial geometry shown in Figure 3.2.

The second step was to determine the mechanical energy required to move 100 m (330 ft). For an X-Y walking beam robot, the worst case would be moving at a 45 degree direction (between the orthogonal frames) effectively requiring 141 m (463 ft) of robot motion.

The third step was applying efficiency assumptions about the electrical and electro-mechanical components of the robot drive system to determine the required battery energy storage. The motor to leg drive mechanism was assumed 60% efficient. An energy conversion efficiency of 85% was assumed for the motors. The motor drive electronics were assumed 90% efficient.

A few other assumption were made in the calculation. These include:

- Buoyancy which would reduce the effective weight of the robot underwater was ignored for the energy consumption estimate. This is a conservative assumption.
- Work done in compressing soil under the robot feet was also ignored. This non-conservative assumption which offsets the first assumption.
- A current velocity of 3 m/s (6 knots) was assumed for estimating hydrodynamic drag. The hydrodynamic drag force was assumed to always act in opposition to robot movement.
- Assumptions were made so that dynamic forces to accelerate and decelerate robot components could be estimated. A foot vertical stroke of .6 m (2 ft) was assumed based on climbing up onto or down off a .25 m (10 in) high obstacle allowing for some foot sinkage. An average velocity and stride length was assumed. The movement cycle time was divided into four equal segments: one segment for raising and lowering legs, one segment for moving the leg set forward, one segment for moving the body and other leg set forward and one segment for computing. Accelerations and decelerations were assumed constant giving inverted "V" shaped velocity profiles for each movement.
- Friction forces were calculated from assumptions about the joint geometry and coefficient of friction and estimated worst case reaction loads at the joint.

The following factors were considered:

Lifting weight of legs

Accelerate and decelerate legs

Friction forces in leg pivots

Accelerate and decelerate when moving leg set forward

Friction in moving a leg set forward

Hydrodynamic forces parallel to motion direction during leg movement

Accelerate and decelerate when moving body and other leg set forward

Friction in moving body and other leg set forward

Hydrodynamic forces parallel to motion direction during body movement

Before estimating the energy consumption, we first need an estimate of the robot weight. Robot weights were estimated based on approximate weights of components. The weight estimate for the beam walker is shown in Table 3.2.

Body Weight		
Battery	13.6 kg	
Computer	3.1 kg	
Explosives	3.4 kg	
Cross bar movement motors 2@4.1 kg	8.2 kg	
Two cross bar mechanism	5.4 kg	
Sensor package	3.5 kg	
Wiring	1.8 kg	
Motor control	1.0 kg	
Input/Output	0.5 kg	
External communication	2.7 kg	
Housing	3.9 kg	
	Body Total	**47.1 kg**
Leg Weight		
Feet 8@0.28 kg	2.2 kg	
Legs 8@0.90 kg	7.2 kg	
Motors 8@2.26 kg	18.1 kg	
Leg lifting mechanism 2@2.70 kg	5.4 kg	
Cross bar 2@1.10 kg	2.2 kg	
Cross bar to leg 2@1.80 kg	3.6 kg	
	Legs Total	**38.7 kg**
	Total Weight	**85.8 kg**

Table 3.2 Beam walker weight estimate

Item	Gait Step	Description	Energy Req'd (Joules)
1	1	Lifting first set of legs (4 legs and feet)	18.1
2	1	Leg pivot friction in lifting first legs	52.2
3	1	Accel/decel. of legs in lifting first legs	0.1
4	2	Accel/decel. in moving first leg set forward	0.1
5	2	Friction in moving first leg set forward	170.2
6	2	Hydrodynamic drag in moving first leg set	227.2
7	3	Leg pivot friction in lowering first set legs	52.2
8	3	Accel/decel. of legs in lowering first set of legs	0.1
9	4	Lifting second set of legs (4 legs and feet)	18.1
10	4	Leg pivot friction in lifting second set of legs	52.2
11	4	Accel/decel. of legs in lifting second set of legs	0.1
12	5	Accel/decel. in moving second leg set and body forward	0.5
13	5	Friction in moving second leg set and body forward	192.2
14	6	Leg pivot friction in lowering second set of legs	52.2
15	6	Accel/decel. of legs in lowering second set of legs	0.1
16	6	Hydrodynamic drag in moving second leg set and body	290.5
		Walking energy consumption per stride	**1126.1**

* Formulas for each component of the energy estimate are presented in Appendix B.

Table 3.3 Beam walker energy estimate

The potential energy required to raise the robot 12.2 m (40 ft) is:

$$12.2\text{ m} \times 85.8\text{ kg} \times 9.8\text{ m/s}^2 = 10{,}300\text{ J}$$

Over 141 m (282 strides) travel distance up a 12.2 m slope the energy required is 327,900 J. The energy required is broken down as follows:

Acceleration effort:	271 J
Mechanical work:	10,200 J
Gravitational work:	10,300 J
Friction in mechanism:	161,100 J
Hydrodynamic drag:	146,000 J

Table 3.4 Beam walker energy breakdown

This energy converts to 91.1 watt-hr. The required battery energy is required mechanical energy divided by the combined efficiencies or 198 watt-hrs. Since lead acid batteries can only be discharged to approximately 20%, the required battery capacity is 248 watt-hr. Typical lead acid batteries store 33.1 watt-hr/kg and 0.087 watt-hr/cu cm implying a minimum battery weight of 7.5 kg and 2,850 cu cm. A battery two-thirds larger than this estimate has been allocated and should be sufficient.

There is an interesting conclusion that can be derived from Table 3.4. The acceleration, mechanical and gravitational components are small in comparison to the friction and hydrodynamic components. Therefore, in future design it makes most sense to concentrate on reducing the mechanical friction and minimizing the drag on the system in order to reduce the energy requirements of the robot.

Based on this fact, we reconsidered the tail dragger concept, which rated near the top in the Pugh analysis. This concept, although having different mobility characteristics, would likely have less hydrodynamic drag. The reduced mobility would make it viable only in situations where the sea floor is fairly unobstructed. An advantage here is that the simplicity of the mechanism would likely reduce mechanical friction. This may be offset by the forces required to drag the system across the sea floor. Therefore, we decided to also perform an energy estimate for the tail dragger concept.

Body Weight (same as beam walker)		
	Total Body	**47.1 kg**
Leg Weight		
Feet 2@0.8 lbm	1.6 kg	
Legs 2@1.7 lbm	3.4 kg	
Motors 2@2.2 lbm	4.4 kg	
Leg lifting mechanism 2@0.7 lbm	1.4 kg	
Cross bar	2.2 kg	
Cross bar to leg	2.4 kg	
	Total Legs	**15.4 kg**
	Total Weight	**62.5 kg**

Table 3.5 Tail dragger weight estimate

Item	Description	Energy Req'd (Joules)
1	Lifting legs (2 legs and feet)	9.0
2	Leg pivot friction in lifting legs	26.1
3	Accel/decel. of legs in lifting legs	0.1
4	Accel/decel. in moving leg set forward	0.1
5	Friction in moving leg set forward	85.7
6	Hydrodynamic drag in moving leg set	114.1
7	Leg pivot friction in lowering set legs	26.1
8	Accel/decel. of legs in lowering set of legs	0.1
9	Lifting body partially	11.8
10	Accel/decel. in moving body forward	0.2
11	Friction in moving body forward	301.7
12	Lowering body partially	11.8
13	Hydrodynamic drag in moving second leg set and body	63.2
	Walking energy consumption per stride	**650.0**

* Formulas for each component of the energy estimate are presented in Appendix B.

Table 3.6 Tail dragger energy estimate

The potential energy required to raise the robot 12.2 m (40 ft) is:

$$12.2 \text{ m} \times 62.5 \text{ kg} \times 9.8 \text{ m/s}^2 = 7{,}480 \text{ J}$$

Over 141 meters (308 strides) travel distance up a 12.2 m slope the energy required is 207,700 J or 57.8 watt-hr. The required battery energy is required mechanical energy divided by the combined efficiencies or 126 watt-hrs. This is about half of the energy required for the beam walker, so if the mobility of the tail dragger is sufficient, it does require significantly less power for the mission.

Roughly 30% of the tail dragger energy consumption is due to friction between the robot body and ground at the assumed coefficient of friction of 1.0. It is unlikely that the coefficient of friction will approach 1.0 and, presumably, rolling elements or other means could be added to the robot to reduce the coefficient of friction during body movement. This would either increase robot range or allow the robot to be reduced in size.

3.6 Stability Analysis

Stability analysis determines the ability of a robot to resist tipping over or sliding during operation. Control systems can affect the stability of robots with independent legs by changing the height of the center of gravity and the horizontal distance between the center of gravity and the robot feet. For the two robots under consideration, the kinematics prevent active control of robot stability. This simplifies the stability analysis to a study of static equilibrium. The worst case geometry was selected for analysis. In the underwater environment, hydrodynamic drag forces must be considered in stability analysis.

3.6.1 Beam Walker Stability Analysis

The estimated hydrodynamic drag forces for the beam walker robot are 1005 N (226 lbf) at 3 m/s (6 knot) current velocity. The estimated effective weight of the robot (dry weight - buoyancy) is 543 N (122 lbf). The required foot span at 0.3 m (12 in) of ground clearance is 1.4 m (56 in) to resist overturning. This is larger than the targeted envelope. In addition, the robot is very likely to slide since the shearing drag forces are 1.85 times larger than the normal force. For a sandy cohesionless soil, the apparent coefficient of friction would be expected to be in the range of 0.32 to 0.58 implying allowable applied shear forces of 178 to 316 N (40 to 71 lbf). It should be noted that these coefficients of friction are non-conservative. Some of the shear strength of the soil will be used to support the weight of the robot reducing the allowable horizontal shear force further.

Three options exist to improve this situation. One is to reduce the hydrodynamic drag force by restricting the current velocity specification. The design current velocity would have to be reduced from 3 m/s (6 knots) to 1.25 m/s (2.5 knots) to reach 178 N drag force. Alternatively, the drag coefficients would have to be reduced by 82% to reach 178 N drag force. Ballast could be added to the robot to increase the effective normal force. The effective weight of the robot would have to increased to 3,159 N (707 lbf) to control sliding. This would require a significant increase in the size of robot components to support this additional weight. The size increase would also increase the hydrodynamic drag forces, potentially neutralizing the benefit. A third option would be to actively anchor the robot feet to the sea floor. The use of any of these options would significantly reduce the required foot span to prevent overturning.

Before going forward with more detailed robot design, it is important to develop a better understanding of the soil properties in the expected areas of operation of the robot. Most of the soils where the robots will operate are sedimentary deposits so their properties will be affected by the current velocities that made the deposits. Some soils exhibit cohesive behavior and have shear strength at zero compressive stress. Perhaps, soil shear strengths will be higher in areas of higher current. This is an important area for future consideration.

3.6.2 Tail Dragger Stability Analysis

The estimated hydrodynamic drag forces for the tail dragger robot are 387 N (87 lbf) at 3 m/s (6 knot) current velocity. The estimated effective weight of the robot (dry weight - buoyancy) is 323 N (72.6 lbf). The required foot span is 0.42 m (16.4 in) to resist overturning. As with the beam walker, the robot is likely to slide since the shearing drag forces are 1.2 times larger than the normal force.

The same options exist to improve this situation. The design current velocity would have to be reduced from 3 m/s (6 knots) to 1.7 m/s (3.4 knots) to reach 102 N (23 lbf) drag force. Alternatively, the drag coefficients would have to be reduced by 73% to reach 102 N drag force. Ballast could be added to the robot to increase the effective normal force. The effective weight of the robot would have to increased to 1,210 N (272 lbf) to control sliding.

3.7 Control Systems And Strategy

Control systems for walking robots are typically structured in a hierarchical functionality. Higher level functions include navigation and path planning. The lowest level controls the mechanics of the walking motion. A similar control system structure will be used for these underwater walking robots.

The particular control system strategy chosen for these robots is the subsumption architecture developed by Rodney Brooks at the Massachusetts Institute of Technology's Artificial Intelligence Laboratory. This architecture consists of a series of interacting "behavior" modules which control the robot. As new control requirements are identified, new behavior modules can be easily added to the existing set of behavior modules to increase functionality.

The higher level control requirements for underwater walking robots are conceptually equivalent to those of robots moving on dry land. Therefore, similar control strategies can be used for navigation and path planning. The capabilities of these control strategies are limited by the amount of environmental information available from stored databases and sensory inputs and the available computing power.

A simple navigation and path planning strategy was selected for these underwater walking robots in response to the environment sensing difficulties and desire for low robot cost. The principle behaviors selected to be included in our subsumption implementation are:

1. Basic foot motion. Initial evaluation concluded that the following inputs would be sufficient to control vertical foot motion:

- foot contact with surface detection
- leg maximum up position detection
- leg displacement measurement

In operation, each foot would be driven down from the up position until contact is made with the surface. The height and orientation of the body would be determined from the foot displacement information after all feet have made contact. Corrections in orientation could then be made. If a foot or feet reached their maximum down travel without making contact, an error would exist and corrective action taken to change foot fall positions. Foot displacement could be determined by time from movement start to foot contact assuming constant foot velocity or by counting foot vertical travel actuator motor revolutions.

2. Obstacle Avoidance. When the robot bumps into an obstacle, this behavior directs the machine to back-up slightly, shift laterally and try again.

3. Obstacle Avoidance Monitor. This module takes over when it senses that the obstacle avoidance module has iterated too many times without finding a solution. The monitor directs the robot to back-up further and make an estimated 90° turn from the original direction.

4. General Direction Control. This behavior drives the robot in a particular compass heading. It is temporarily over-ridden when the Obstacle Avoidance behavior takes over, but will eventually restore the robot to the desired course.

Two additional objectives were defined for the beam walker control system. One is to maintain the body of the robot roughly parallel to the walking surface to reduce hydrodynamic lift effects. The second is to minimize vertical oscillation of the body during walking to reduce energy consumption.

Inputs/Outputs

The definition of a control system requires two things, a list of the system inputs and desired outputs and the relationships between those inputs and outputs. The types of inputs and outputs for the beam walker and the tail dragger are similar, although the beam walker will have more due to the additional legs. Typical inputs and outputs are shown in Table 3.7.

Control System Inputs	Control System Outputs
For each leg assembly:	For each leg assembly:
Leg up travel limit switch	Leg motor up
Leg down travel limit switch	Leg motor down
Leg up-down motor rotations	Leg motor forward
Leg forward travel limit switch	Leg motor rearward
Leg rearward travel limit switch	
Leg forward-rearward motor rotations	Detonate explosive
Foot ground contact switch	Explosive arming state
Foot bump switch	Robot system status
	Battery charge status
Robot body front bump switch(es)	Communication ("I've found a mine.
Robot body rear bump switch(es)	Go find your own.") to other robots
Robot body right side bump switch(es)	
Robot body left side bump switch(es)	
Battery state	
Sensor package inputs	
Communications input	
Mission information (heading, etc. loaded before mission)	
Near mine communication from other robots	

Table 3.7 Typical inputs and outputs

The control system hardware is based on a semi-custom microcontroller board. A board derived from RedZone's Distributed Control System Node Cards will be used. These boards are based on a Motorola 68HC16 microprocessor and are capable of interfacing with digital as well as analog signals. The card can be configured for a maximum of 14 digital inputs/outputs or a combination of inputs and outputs. The digital input/output lines can be used to monitor external switch settings and to control external power devices. By using the special functions available to some of the I/O lines, the period and/or pulse width of the input signal can be determined. Also, when using these special functions, an I/O line can generate a periodic pulse of a specific frequency and duty cycle. All of this functionality is contained in a board that is approximately the size of a cigarette pack.

Custom interfacing for the specific sensors and actuators on the wave-walker can be added to the basic Node card design for the wave-walker application. This will provide a well-established design that meets the specialized demands of the wave-walker.

Chapter 5: Further Investigation

A better understanding of the operating environmental conditions for the robot is needed. Topography and soil mechanics properties are needed to determine the mobility requirements for the robots. Water current directions and strengths also need to be understood because of their effect on hydrodynamic drag forces.

Presumably, these robots will be used in areas where amphibious landings are feasible. Allowable environmental conditions for amphibious landing beaches are restricted by the capabilities of the equipment and men used in the landing. These restrictions should reduce the mobility requirements for these robots.

Understanding of the soil mechanics properties of the walking surfaces will affect foot size and geometry. The foot soil interaction will affect robot stability through soil bearing strength and the hydrodynamic drag of the feet. The topography of the walking surface will affect the control system design for navigation and obstacle handling.

Additional investigation of battery systems is needed. Other battery systems should give increased range but the cost and other implications need to be understood. Since these robots will be single use devices, it seems unnecessary to use a rechargeable battery.

The hydrodynamic design of the robot will be important because of the effect of hydrodynamic drag on stability and energy consumption. The hydrodynamic design of the robot will have to be symmetric since the current can be from any direction. The hydrodynamic design will be difficult due to the bluff body shapes of the robot components and the complex flow patterns of the interacting shapes.

Appendix A: Selection Criteria Refinement

The following outline illustrates how the selection criteria were refined into more fundamental robot attributes.

Selection Criteria	Robot Attribute
Robot cost	*Total number of leg links*
Control complexity	*Leg link complexity*
Energy consumption	*Total number of actuators*
Maximum travel velocity	*Number of coordinated actuator motions to achieve movement*
Stability	*Open or closed loop control of actuators*
Maneuverability	*Vertical oscillation of body mass during movement*
Ease of waterproofing	*Friction during movement*
	Stride length
	Drag area of leg links
	Total weight/foot size (for legs in contact)
	Ease of sealing out water (rotary actuators are easier to seal)

Table A.1 Selection criteria and robot attributes

I. **Robot cost** determined by

- A. Leg cost determined by
  1. *Total number of leg links*
  2. *Leg link complexity*
  3. *Total number of actuators*

- B. Body cost almost constant affected by
  - 1. Control complexity determined by
    - a. *Total number of actuators*
    - b. *Number of coord. actuator motions to achieve mov't*
    - c. *Open or closed loop control of actuators*
  - 2. Energy storage size determined by
    - a. Energy consumption determined by
      - 1) *Total number of actuators*
      - 2) *Vertical oscillation of body mass during movement*
      - 3) *Friction during movement*

II. **Control complexity** determined by

- A. *Total number of actuators*
- B. *Number of coordinated actuator motions to achieve movement*
- C. *Open or closed loop control of actuators*

III. **Energy consumption** determined by

- A. *Total number of actuators*
- B. *Vertical oscillation of body mass during movement*
- C. *Friction during movement*
- D. *Drag area of leg links*

IV. **Maximum travel velocity** determined by

- A. Control complexity determined by
  - 1. *Total number of actuators*
  - 2. *Number of coordinated actuator motions to achieve movement*
  - 3. *Open or closed loop control of actuators*
- B. *Stride length*

V. **Stability** determined by

  A. Hydrodynamic drag of legs determined by

    1. *Total number of leg links*

    2. *Drag area of leg links*

  B. Foot sinkage determined by

    1. *Total weight/foot size(for legs in contact)*

VI. **Maneuverability** determined by

  A. *Total number of actuators*

  B. Control complexity determined by

    1. *Total number of actuators*

    2. *Number of coordinated actuator motions to achieve movement*

    3. *Open or closed loop control of actuators*

VII. **Ease of waterproofing**

  A. *Ease of sealing out water (rotary actuators are easier to seal)*

Appendix B: Energy Estimate Formulas

Below are the formulas used to generate the energy estimates for the robot concepts.

B.1 Beam Walker

1. Lifting first set of legs (4 legs and feet)

4 x foot weight x 0.61 m + 4 x leg weight x moment arm x rotation angle = 18.1 J

2. Leg pivot friction in lifting first legs

4 x friction torque x rotation angle = 52.2 J

3. Accel/decel. of legs in lifting first legs

4 x (leg inertia + foot inertia) x angle of rotation squared / mov't time squared = 0.1 J

Note: this equation comes from applying the assumptions of 25% of movement cycle time being used for leg movement and constant acceleration and deceleration. The 25% time segment is further subdivided into equal quarters, one for each leg movement up or down. It also assumes that no energy regeneration takes place.

4. Accel/decel. in moving first leg set forward

64 x avg. robot velocity squared x mechanism mass = 0.1 J

Note: this equation comes from applying the assumptions of 25% of movement cycle time being used for leg set movement and constant acceleration and deceleration. It also assumes that no energy regeneration takes place.

5. Friction in moving first leg set forward

coefficient of friction x leg set weight x stride + coefficient of friction x overturning moment reaction x stride = 170.2 J

6. Hydrodynamic drag in moving first leg set

(hydrodynamic drag of feet + hydrodynamic drag of legs) x stride length = 227.2 J

Assume:

drag coefficient of feet = 1.1

drag coefficient of legs = 0.6

7. Leg pivot friction in lowering first set legs

2 x friction torque x rotation angle = 52.2 J

8. Accel/decel. of legs in lowering first set of legs

4 x (leg inertia + foot inertia) x angle of rotation squared / mov't time squared = 0.1 J

Note: this equation comes from applying the assumptions of 25% of movement cycle time being used for leg movement and constant acceleration and deceleration. The 25% time segment is further subdivided into equal quarters, one for each leg movement up or down. It also assumes that no energy regeneration takes place.

9. Lifting second set of legs (4 legs and feet)

4 x foot weight x 0.61 m + 4 x leg weight x moment arm x rotation angle = 18.1 J

10. Leg pivot friction in lifting second set of legs

2 x friction torque x rotation angle = 52.2 J

11. Accel/decel. of legs in lifting second set of legs

4 x (leg inertia + foot inertia) x angle of rotation squared / mov't time squared = 0.1 J

Note: this equation comes from applying the assumptions of 25% of movement cycle time being used for leg movement and constant acceleration and deceleration. The 25% time segment is further subdivided into equal quarters, one for each leg movement up or down. It also assumes that no energy regeneration takes place.

12. Accel/decel. in moving second leg set and body forward

64 x avg. robot velocity squared x mechanism mass = 0.5 J

Note: this equation comes from applying the assumptions of 25% of movement cycle time being used for leg set movement and constant acceleration and deceleration. It also assumes that no energy regeneration takes place.

13. Friction in moving second leg set and body forward

coefficient of friction x leg set weight x stride + coefficient of friction x overturning moment reaction x stride = 192.2 J

14. Leg pivot friction in lowering second set of legs

2 x friction torque x rotation angle = 52.2 J

15. Accel/decel. of legs in lowering second set of legs

4 x (leg inertia + foot inertia) x angle of rotation squared / mov't time squared = 0.1 J

Note: this equation comes from applying the assumptions of 25% of movement cycle time being used for leg movement and constant acceleration and deceleration. The 25% time segment is further subdivided into equal quarters, one for each leg movement up or down. It also assumes that no energy regeneration takes place.

16. Hydrodynamic drag in moving second leg set and body

(hydrodynamic drag of feet + hydrodynamic drag of legs + hydrodynamic drag of body) x stride length = 290.5 J

Assume:

drag coefficient of feet = 1.1

drag coefficient of legs = 0.6

drag coefficient of body = 0.5

B.2 Tail Dragger

1. Lifting legs (2 legs and feet)

2 x foot weight x 0.61 m + 2 x leg weight x moment arm x rotation angle = 9 J

2. Leg pivot friction in lifting legs

2 x friction torque x rotation angle = 26.1 J

3. Accel/decel. of legs in lifting legs

2 x (leg inertia + foot inertia) x angle of rotation squared / mov't time squared = 0.1 J

Note: this equation comes from applying the assumptions of 25% of movement cycle time being used for leg movement and constant acceleration and deceleration. The 25% time segment is further subdivided into equal quarters, one for each leg movement up or down. It also assumes that no energy regeneration takes place.

4. Accel/decel. in moving leg set forward

64 x avg. robot velocity squared x mechanism mass = 0.1 J

Note: this equation comes from applying the assumptions of 25% of movement cycle time being used for leg set movement and constant acceleration and deceleration. It also assumes that no energy regeneration takes place.

5. Friction in moving leg set forward

coefficient of friction x leg set weight x stride + coefficient of friction x overturning moment reaction x stride = 85.7 J

6. Hydrodynamic drag in moving leg set

(hydrodynamic drag of feet + hydrodynamic drag of legs) x stride length = 114.1 J

Assume:

drag coefficient of feet = 1.1

drag coefficient of legs = 0.6

7. Leg pivot friction in lowering set legs

2 x friction torque x rotation angle = 26.1 J

8. Accel/decel. of legs in lowering set of legs

4 x (leg inertia + foot inertia) x angle of rotation squared / mov't time squared = 0.1 J

Note: this equation comes from applying the assumptions of 25% of movement cycle time being used for leg movement and constant acceleration and deceleration. The 25% time segment is further subdivided into equal quarters, one for each leg movement up or down. It also assumes that no energy regeneration takes place.

9. Lifting body partially

body weight x 0.025 m = 11.8 J

10. Accel/decel. in moving body forward

64 x avg. robot velocity squared x mechanism mass = 0.2 J

Note: this equation comes from applying the assumptions of 25% of movement cycle time being used for leg set movement and constant acceleration and deceleration. It also assumes that no energy regeneration takes place.

11. Friction in moving body forward

coefficient of friction x body weight x stride + coefficient of friction x overturning moment reaction x stride = 301.7 J

Assumes body to ground coefficient of friction = 1.

12. Lowering body partially

body weight x 0.025 m = 11.8 J

13. Hydrodynamic drag in moving second leg set and body

hydrodynamic drag of feet x stride length = 63.2 J

Assume drag coefficient of feet = 0.5